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Identification of cryovolcanism on Titan using fuzzy cognitive maps

Roberto Furfaro [a,*], Jeffrey S. Kargel [b], Jonathan I. Lunine [c], Wolfgang Fink [d,e], Michael P. Bishop [f]

[a] Aerospace and Mechanical Engineering Department, University of Arizona, Tucson, AZ 85721, USA
[b] Department of Hydrology and Water Resource, University of Arizona, Tucson, AZ 85721, USA
[c] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[d] Visual and Autonomous Exploration Systems Research Laboratory, Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
[e] Departments of Electrical & Computer Engineering and Biomedical Engineering, University of Arizona, Tucson, AZ 85721, USA
[f] Department of Geography and Geology, University of Nebraska at Omaha, NE 68182, USA

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ABSTRACT

Future planetary exploration of Titan will require higher degrees of on-board automation, including autonomous determination of sites where the probability of significant scientific findings is the highest. In this paper, a novel Artificial Intelligence (AI) method for the identification and interpretation of sites that yield the highest potential of cryovolcanic activity is presented. We introduce the theory of fuzzy cognitive maps (FCM) as a tool for the analysis of remotely collected data in planetary exploration. A cognitive model embedded in a fuzzy logic framework is constructed via the synergistic interaction of planetary scientists and AI experts. As an application example, we show how FCM can be employed to solve the challenging problem of recognizing cryovolcanism from Synthetic Aperture Radar (SAR) Cassini data. The fuzzy cognitive map is constructed using what is currently known about cryovolcanism on Titan and relies on geological mapping performed by planetary scientists to interpret different locales as cryovolcanic in nature. The system is not conceived to replace the human scientific interpretation, but to enhance the scientists' ability to deal with large amounts of data, and it is a first step in designing AI systems that will be able, in the future, to autonomously make decisions in situations where human analysis and interpretation is not readily available or could not be sufficiently timely. The proposed FCM is tested on Cassini radar data to show the effectiveness of the system in reaching conclusions put forward by human experts and published in the literature. Four tests are performed using the Ta SAR image (October 2004 fly-by). Two regions (i.e. Ganesa Macula and the lobate high backscattering region East of Ganesa) are interpreted by the designed FCM as exhibiting cryovolcanism in agreement with the initial interpretation of the regions by Stofan et al. (2006). Importantly, the proposed FCM is shown to be flexible and adaptive as new data and knowledge are acquired during the course of exploration. Subsequently, the FCM has been modified to include topographic information derived from SAR stereo data. With this additional information, the map concludes that Ganesa Macula is not a cryovolcanic region. In conclusion, the FCM methodology is shown to be a critical and powerful component of future autonomous robotic spacecraft (e.g., orbiter(s), balloon(s), surface/lake lander(s), rover(s)) that will be deployed for the exploration of Titan.

1. Introduction

Autonomy will be a critical factor in enabling future science-driven and less constrained planetary reconnaissance of remote bodies (e.g., Titan and Europa). Indeed, the exploration of the outer planets of the Solar System and their moons has the potential to yield a large wealth of geological and possibly exobiological information. Lately, these planetary bodies received a great deal of attention from NASA, ESA, and other space agencies around the world. Established by NASA in 2004, the Outer Planet Assessment Group (OPAG) identified scientific priorities and pathways for the exploration of the outer Solar System including advocating flagship missions. The goal is to increase our understanding of the outer portion of the Solar System. Flagship mission architectures may be comprised of single or multiple agents (e.g., orbiter(s), balloon(s), lander(s), rover(s)) and may be deployed following a tier-scalable reconnaissance architecture (Fink et al., 2005). The agent deployment requires the design, implementation, and integration of an intelligent reconnaissance system (Furfaro et al., 2006, 2007, 2008a,b; Fink et al., 2008). Such system should (1) include software packages that enable fully automated and comprehensive identification, characterization, and quantification of feature information within an operational region, including anomaly detection, with subsequent target

* Corresponding author.
E-mail address: robertof@email.arizona.edu (R. Furfaro).

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prioritization and selection for close-up reexamination (e.g., Automated Global Feature Analyzer, AGFA, Fink et al., 2008; Fink, 2006) and (2) integrate existing information with acquired, ‘‘in transit’’ spatial and temporal sensor data to automatically perform intelligent planetary reconnaissance, which includes identification of sites with the highest potential to yield significant geological and astrobiological information (Furfaro et al., 2008a).

Balloon-borne Titan exploration especially needs a high degree of autonomous operation and interpretation, because a well-instrumented balloon without a well-designed intelligent system may overfly and pass up areas of highest scientific interest before Earth-based observers are even aware of the interesting encounter, as discussed below.

To address such challenges, expertise from the field of Artificial Intelligence (AI) must be integrated with expert knowledge residing within the planetary science community. Novel tools must be developed (a) that may be implemented on on-board processors of the respective agents to autonomously identify geological features and (b) that may provide autonomous interpretation of the geologic and exobiologic content exhibited by the observed locale. Various AI methods and techniques are available to tackle such a challenging problem. Generally speaking, designing an intelligent system that reasons over data mimicking the planetary scientist approach requires two fundamental ingredients: knowledge and inference representation. Planetary science knowledge can be represented by rules or methods from which it is possible to perform plausible reasoning to obtain new facts and hypotheses. Knowledge must be coupled with an inference mechanism, defined as the process of matching data and knowledge to infer new information. The way knowledge and inference are integrated into AI algorithms marks the difference between the various approaches. For example, symbolic AI, fuzzy logic-based and neural networks-based schemes provide different frameworks that can generate intelligent systems for planetary exploration. Neural networks fall under the category of connectionist systems. In such cases, knowledge is distributed among various nodes. Indeed, neural networks are constructed in such a way that knowledge is unstructured as they learn by examples, by doing or by analogy. Moreover, they are capable of good generalization and adaptation. Conversely, symbolic AI and fuzzy systems are conceived and designed to represent structured knowledge, i.e. knowledge is captured via rules that are defined either symbolically or that are directly derived from the human language. Whereas inference is exact in symbolic AI, it is approximate in fuzzy-based and neural network systems. Symbolic AI systems do not deal very well with missing, corrupted, and inexact data.

Fuzzy logic has been recently considered as premiere AI technique to mimic human reasoning over planetary science data (Furfaro et al., 2008a,b). For example, Furfaro et al. (2008b) have tackled the problem of designing and implementing intelligent systems capable of autonomous reasoning while performing science-driven reconnaissance of Titan and Enceladus. Previous work showed that fuzzy logic can be an attractive and effective framework to implement expert knowledge while looking for life (Furfaro et al., 2008a) or following the water (Furfaro et al., 2006). Fuzzy cognitive maps (FCMs) are an attractive knowledge-based Artificial Intelligence (AI) methodology that merges fuzzy logic and neural network properties (Stylios and Groumpos, 2000). FCMs employ a soft computing technique (Kosko, 1986; Stylios and Groumpos, 2004) that was conceived to deal with uncertain and fuzzy concept description using similar procedures employed by human reasoning (Papageorgiou et al., 2004) on the basis of knowledge and experience derived from a particular field of study. The required knowledge is structured using an array of concepts and a web of relationships between them. Such techniques have been employed in a large variety of fields including biomedical and other engineering areas. For example, FCMs have been successfully used in modeling supervisory control systems for industrial applications (Stylios and Groumpos, 2004), causal inference (Miao and Liu, 2000), in modeling and analyzing radiotherapy processes (Papageorgiou et al., 2003), in modeling the process of selecting brain tumors (Papageorgiou et al., 2008), and in managing nuclear power plants (Espinosa-Paredes et al., 2008).

In this paper, we develop FCMs as an intelligent system capable of identifying cryovolcanism on Titan. The fuzzy-based scheme is designed to reason over the Cassini Synthetic Aperture Radar (SAR) image data (Elachi et al., 2005) and determine if cryovolcanism is present in the observed region. The system employs concepts and a web of causal connections to mimic the inference process executed by planetary scientists to interpret/identify the geological processes shaping Titan’s surface. Some interesting features of FCMs that we wish to exploit are their flexibility in modeling and design, their ability to abstractly represent the behavior of complex systems, and their ability to change an interpretation when newly added data direct the FCM to a different assessment of probability.

Cryovolcanism has been hypothesized to occur on the largest saturnian satellite based on radar data (Stofan et al., 2006; Lopes et al., 2007), but it is unknown to what extent this process has shaped Titan’s surface. It is our goal to introduce cognitive models into the planetary science community to show how human-like reasoning may be effectively implemented to perform intelligent planetary reconnaissance. Importantly, although based on a similar AI framework, FCMs represent an alternative to fuzzy-based expert systems that have been designed to perform similar human-like reasoning (Furfaro et al., 2008a,b). Fuzzy expert systems capture field knowledge using rules coded in a linguistic fashion and employ the methods of fuzzy logic to perform inference. Designing such systems requires that AI experts work with planetary scientists to define the proper IF-THEN rules that capture the understanding of a specific process. Ultimately, a knowledge-base is defined as a collection of linguistic rules that capture what is known about the problem. Conversely, as discussed above, FCMs capture knowledge using concepts spread across a map linked by a web of causal connections that defines what is understood about the specific process that is modeled. At this stage, we believe that both approaches are valid. Here, our goal is to show how FCMs can be designed to reason over cryovolcanism and we highlight the effectiveness of such methodology. This work may stimulate research on defining other AI approaches that may be critical for planetary exploration.

The paper is organized as follows. In Section 2, a theoretical background is provided. Cryovolcanism on Titan is described and a brief introduction to the concept of FCMs is provided. After discussing the need for cognitive models for the exploration of Titan, the process of constructing, implementing, and testing a FCM for autonomous identification of cryovolcanism on Titan is described in Section 3. Section 4 reports on four case studies where the designed FCM is tested against Cassini SAR images to show that the proposed system reasons like planetary scientists by correctly reproducing human interpretations of the examined areas as cryovolcanic, according to the planetary science literature (e.g., Lopes et al., 2007). Section 5 shows how FCMs can be modified to account for new knowledge and effectively can produce a change of interpretation or a reinforcement of a prior interpretation as new data and new concepts are added. Section 6 reports discussion and conclusions.